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De-excitation of the strongly coupled band in ^{177}Au and implications for core intruder configurations in the light Hg isotopes

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Excited states in the proton-unbound nuclide ^{177}Au were populated in the ^{92}Mo(^{88}Sr, $p2n$) reaction and identified using the Jurogam-II and GREAT spectrometers in conjunction with the RITU gas-filled separator at the University of Jyväskylä Accelerator Laboratory. A strongly coupled band and its decay path to the $11/2^-$ α-decaying isomer have been identified using recoil-decay tagging. Comparisons with cranked Hartree-Fock-Bogoliubov (HFB) calculations based on Skyrme energy functionals suggest that the band has a prolate deformation and is based upon coupling the odd $1h_{11/2}$ proton hole to the excited 0_2^+ configuration in the ^{178}Hg core. Although these configurations might be expected to follow the parabolic trend of core Hg(0_2^+) states as a function of neutron number, the electromagnetic decay paths from the strongly coupled band in ^{177}Au are markedly different from those observed in the heavier isotopes above the midshell. This indicates that a significant change in the structure of the underlying $^{A+1}$Hg core occurs below the neutron midshell.

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The complexities of the atomic nucleus as a many-body system arise from the interplay between single-particle and collective degrees of freedom. This is particularly apparent in heavy nuclei near closed shells where near degenerate spherical and deformed intrinsic configurations can coexist at low-excitation energies. This shape coexistence arises from the opposing tendencies of shell structure and residual interactions that promote sphericity and deformation, respectively, and is especially sensitive to the arrangement of nucleons at the Fermi surface.

Shape coexistence in nuclei near the $Z = 82$ closed shell was first apparent from the unexpected isotope shifts between ^{185}Hg and ^{187}Hg measured using optical hyperfine spectroscopy [1]. Subsequent in-beam and decay experiments revealed excited 0^+ states in the even-mass $180 \leqslant N \leqslant 190$ Hg isotopes, which were interpreted in terms of weakly deformed ground states and strongly deformed intruder configurations based on proton-pair excitations across the $Z = 82$ shell gap [2]. This interpretation has been confirmed experimentally in recent Coulomb excitation measurements using accelerated radioactive ion beams [3].

The excited 0^+ state energies in the Hg isotopes exhibit a well-established parabolic dependence on neutron number with a minimum at $N = 102$ near the neutron midshell between $N = 82$ and $N = 126$. However, recent mean-field calculations suggest that the smooth parabolic behavior of the excited 0^+ states in the Hg isotopes may hide differences in the shape of the underlying potentials whence these states have their origin [4]. Indeed, these calculations predict that the relative excitation energies of the oblate and prolate minima could be exchanged in the highly neutron-deficient Hg isotopes. Both proton-particle and proton-hole configurations are observed in odd-Au isotopes. Proton holes couple to even-even Hg cores, while proton particles couple to even-even Pt cores, resulting in distinct groups of states [5]. Therefore, one method for revealing subtle structural differences in the Hg isotopes is to identify excited states in their odd-mass

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Au isotones where the odd proton hole couples to the Hg core configurations. The analogous excited hole states in the Au isotopes that couple to Hg cores have been observed in ^{185}Au$_{106}$ and ^{187}Au$_{108}$ [6,7] but not in others.

In this work, we report the detailed characterization of a strongly coupled band with $K = \Omega = 11/2$ (13/2) in the proton-unbound nucleus ^{177}Au, which exhibits low rotational alignment relative to the underlying ^{178}Hg core. These results are interpreted in terms of mean-field calculations and the implications for the structure of the highly neutron-deficient Hg cores are discussed. The strongly coupled band was first observed in a prior experiment by Kondev *et al.* [8,9]. Reference [8] showed singles γ-ray spectra tagged by the two low-lying α-decaying states in ^{177}Au while level schemes, energies, and intensities were presented in Ref. [9]. In the present work, we present γ-ray coincidence spectra, which augment the known level scheme. Newly identified transitions feeding low-spin states and comparison of the strongly coupled band with the intruder bands in ^{176}Pt and ^{178}Hg lead us to propose alternative spin assignments for the strongly coupled band. The absence of strongly coupled bands with similar decay paths to the low-spin states in the heavier odd-mass Au isotopes indicates a significant difference in the nature of the deformed even-Hg core structure between $A = 178$ and 184. We note that there is another well-developed strongly coupled band in ^{181}Au$_{102}$ [10] originating from the same configuration. However, the excitation energy of this band cannot be established firmly due to the proximity of ^{181}Au to the neutron midshell, which presumably places the $K = \Omega = 11/2$ band head very close to the $11/2^-$ isomeric state.

The experiment was performed at the University of Jyväskylä Accelerator Laboratory. A beam of ^{88}Sr^{10+} ions with an energy of 399 MeV and average intensity of approximately 2 particle nA was delivered by the $K = 130$ MeV cyclotron and impinged on a target inducing fusion-evaporation reactions. Self-supporting metallic targets with a thickness of 0.6 mg/cm^2 were prepared from isotopically enriched material of ^{92}Mo (98% enrichment). The total irradiation time was approximately 230 h. Fusion evaporation residues were separated from the the scattered primary beam and fission products according to their different magnetic rigidities by the gas-filled recoil separator RITU [11]. After separation, the evaporation residues passed through the multiwire proportional counter (MWPC) and were implanted into the double-sided silicon strip detectors (DSSD) of the focal-plane spectrometer GREAT [12]. Recoiling evaporation residues were distinguished from the scattered beam and subsequent radioactive decays by energy loss in the MWPC and, in conjunction with the DSSD, time-of-flight information. γ rays emitted promptly at the target position were detected by the JUROGAM-II array, consisting of 24 clover- and 15 EUROGAM-type Compton suppressed spectrometers. The time-stamped stream of data was acquired from each detector independently using the total data readout digital data acquisition system [13]. Data were sorted offline and analysed using the GRAIN [14] and RADWARE [15] software analysis packages.

Two α-decaying states are known in ^{177}Au: the ground state, which was assigned spin-parity $1/2^{(+)}$ [16], and an excited state at 189(16) keV, with spin parity $(11/2^-)$ [17]. In addition, the yrast sequence associated with the $1i_{13/2}$ intruder configuration has been identified in an earlier in-beam γ-ray spectroscopy experiment [18]. Well-separated energies of α particles emitted from ground and isomeric states ($E_\alpha^{g.s.} =$ 6167 keV and $E_\alpha^{i.s.} = 6124$ keV [17]), together with relatively short half-lives ($T_{1/2}^{g.s.} = 1.46$ s and $T_{1/2}^{i.s.} = 1.18$ s [17]), make ^{177}Au suitable for recoil-decay tagging. In this technique, γ rays detected at the target position are identified through spatial and temporal correlations with recoil implantations at the separator focal plane and their subsequent characteristic radioactive decays [19,20].

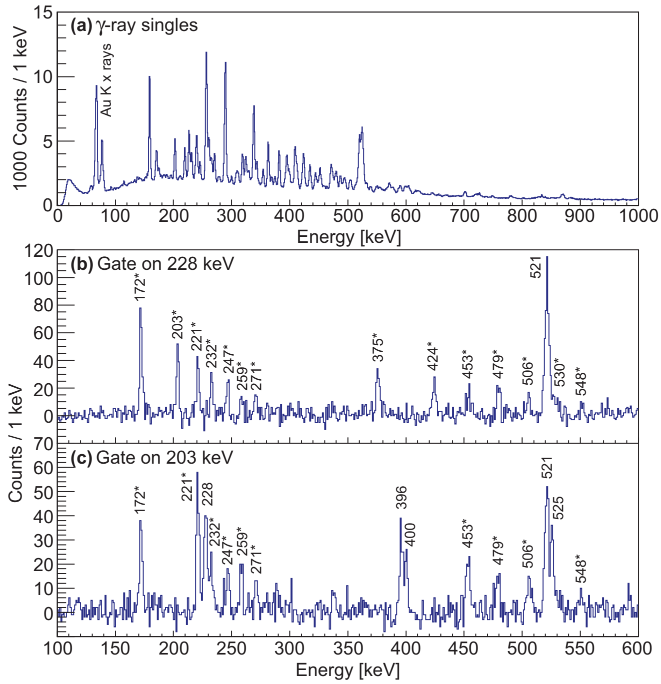

FIG. 1. γ-ray spectra measured with the JUROGAM-II spectrometer. Spectra showing γ rays correlated with ion implantations followed by the characteristic α decay the $11/2^-$ isomer in ^{177}Au ($E_\alpha = 6124$ keV) within the same DSSD pixel of the GREAT spectrometer. The recoil-α correlation time was limited to 3 s. (a) γ-ray singles spectrum, while panels (b) and (c) show γ rays in coincidence with 228- and 203-keV transitions. γ rays assigned to the strongly coupled band in ^{177}Au are labeled by their transition energies. Inband transitions are highlighted with an asterisk.

Figure 1(a) shows the energy spectrum of γ rays associated with the decay of the $11/2^-$ isomer, which were identified recoil-decay correlations with the corresponding α particles. The spectrum is dominated by the de-excitations of the known $1i_{13/2}$ cascade. Two γ-ray transitions at 228 and 203 keV were identified as feeding the $11/2^-$ isomer. The spectra of the γ rays in coincidence with these transitions are shown in Figs. 1(b) and 1(c). Spectra show monotonic sequences of $M1/E2$ and $E2$ in-band transitions together with several linking transitions. The γ-ray coincidence analysis revealed that these transitions form a strongly coupled band that is placed unambiguously in the energy level scheme; see Fig. 2. Hereafter, the excitation energies of all states are quoted relative to the $11/2^-$ α decaying isomer.

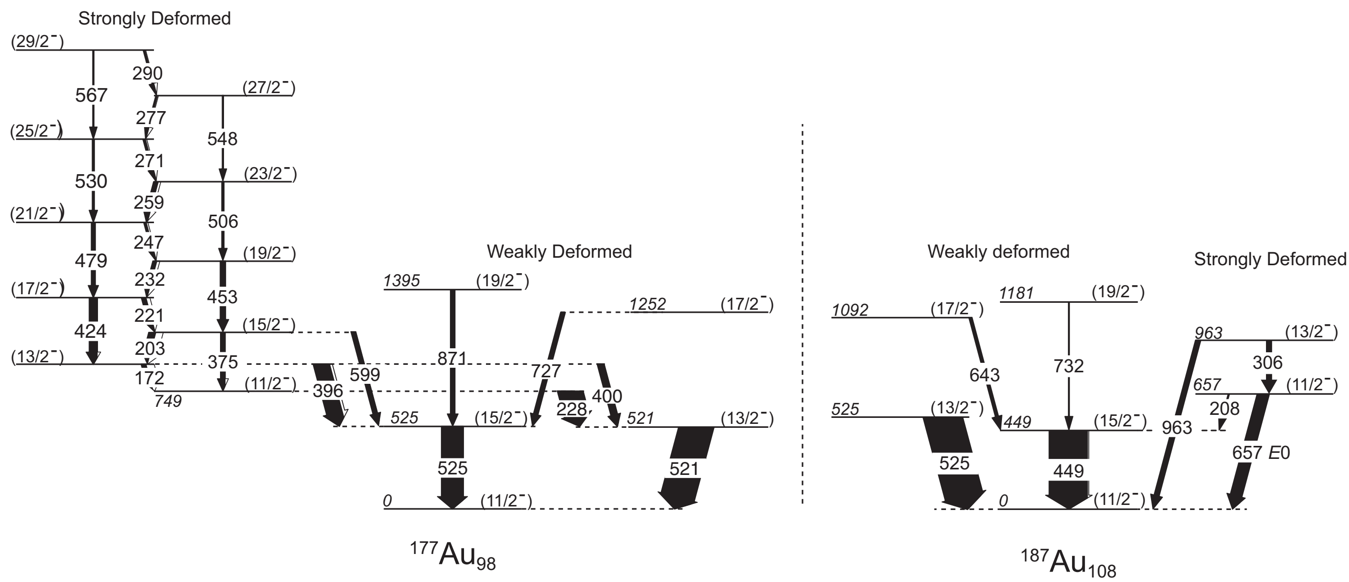

FIG. 2. Level scheme of the states associated with $1h_{11/2}$ proton-hole configuration in ^{177}Au deduced in the present work compared with the analogous spherical and deformed configurations in the heavier isotope ^{187}Au. Level excitation energies are stated relative to the $11/2^-$ state. The decay paths from the deformed structures to their respective $11/2^-$ states are different in the two isotopes.

The strongly coupled band decays exclusively to the $11/2^-$ isomer via two intermediate states at 521 and 525 keV. The 521- and 525-keV γ rays depopulating these states have similar energies to the $2_1^+ \rightarrow 0_1^+$ transition in ^{178}Hg (558 keV) [21] and are likely to be configurations formed by coupling $1h_{11/2}$ proton holes to the weakly oblate ^{178}Hg core. The multipolarity of the 521-keV γ ray was determined using directional correlations from oriented states [22] and is consistent with a $\Delta I = 1$ transition [$R_{DCO} = 0.6(1)$] leading to possible spin assignments of 9/2 or 13/2 for the initial state. The level energies associated with the $1h_{11/2} \otimes^{A+1}$ Hg configurations in odd-Au isotopes are established from the line of stability to beyond the proton drip line and vary smoothly as a function of neutron number [23–25]. These systematic trends favor the $13/2^-$ assignment for the 521-keV level. The 525-keV level is fed by 727- and 871-keV γ rays and has a similar feeding pattern to that observed in the heavier odd-mass Au isotopes where γ rays depopulating the $17/2^-$ and $19/2^-$ states feed the $15/2^-$ state strongly. This similarity favours a $15/2^-$ spin-parity assignment for the 525-keV state.

Based on the K x-ray intensity balance, a conversion coefficient for the 228-keV transition of 0.58(23) was deduced, which compares well with the BRICC estimates for a pure $M1$ transition of 0.588(9) [26]. Within the experimental uncertainty an $E2$ admixture cannot be excluded. Moreover, the subsequent intensity balance between the transitions feeding the $(13/2^-)$ state with the 521-keV transition that depopulates it implies that there is no significant $E0$ component in the latter transition. The absence of a strong $E0$ component suggests that the 521-keV transition is not a $J \rightarrow J$ transition, which further supports the $(13/2^-)$ assignment for the 521-keV level. The nature of the other decay paths from the strongly coupled band and the absence of other γ-ray transitions feeding the $11/2^-$ isomer directly constrains the lowest observed level in the strongly coupled band to be either $11/2^-$ or $13/2^-$. It was not possible to constrain the multipolarities of other transitions in the same way. Although a tentative $11/2^-$ assignment is proposed for the band head of the strongly coupled band in Fig. 2, a $13/2^-$ assignment would not materially affect the conclusions drawn below.

The γ-ray energies of the strongly coupled band in ^{177}Au are plotted as a function of the initial state angular momentum, assuming that the 749-keV level is the $11/2^-$ band head, alongside the prolate bands of its neighboring isotones ^{178}Hg [21,27] and ^{176}Pt [28] in Fig. 3(a). The curves for the ^{177}Au band are almost identical to those of the prolate bands in the even-mass isotones ^{178}Hg and ^{176}Pt. The strongly coupled band in ^{177}Au band is assigned to be a configuration formed by the coupling of the $1h_{11/2}$ proton hole to the unobserved well-deformed excited 0^+ state in the ^{178}Hg core. The moments of inertia extracted for this configuration and the small signature splitting are consistent with a well-deformed axial prolate shape.

The $1h_{11/2}^{-1} \otimes {}^{178}\mathrm{Hg}(0_2^+)$ configuration in ^{177}Au is markedly different from analogous configurations in the heavier Au isotopes whose energies as a function of the neutron number should lie on a similar parabola to that established for the 0_2^+ states in the Hg core [2]. The structures of $1h_{11/2}^{-1} \otimes^{A+1} \mathrm{Hg}(0_2^+)$ configurations have been studied in ^{185}Au and ^{187}Au [6,7] by conversion-electron-γ-ray coincidence measurements [29]. In these isotopes, the deformed $11/2^-$ and $13/2^-$ states decay predominantly to the near-spherical $11/2^-$ member of the $1h_{11/2} \otimes {}^{A+1}\mathrm{Hg}(0_1^+)$ proton-hole configuration. It should be noted that the $J \rightarrow J$ decay paths in these nuclei have strong electric monopole ($E0$) components [6,7]. This is not the case in ^{177}Au, where the decay proceeds through pairs of levels with spin $(13/2^-)$ and $(15/2^-)$ and not directly to the near spherical $11/2^-$ level; see Fig. 2. This indicates that there is no strong electromagnetic coupling between the strongly coupled band and the weakly deformed states and that the 0_2^+ state in the corresponding Hg core has a different structure in ^{177}Au. We

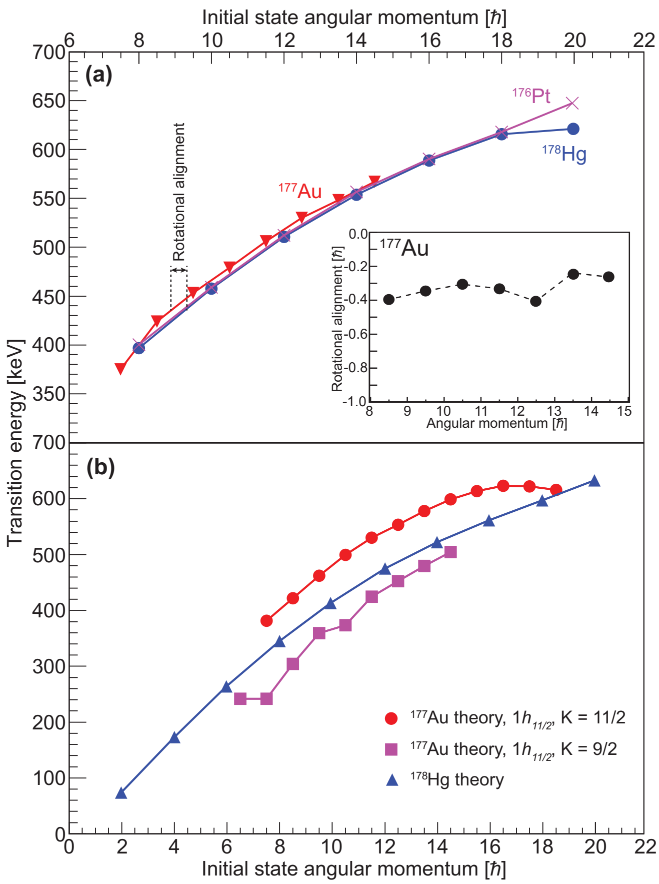

FIG. 3. (a) γ-ray energies as a function of initial state angular momentum for $E2$ transitions in the ^{177}Au strongly coupled band, ^{178}Hg and ^{176}Pt intruder bands. The inset gives the rotational alignment calculated as shift of the ^{177}Au curve relatively to ^{178}Hg. (b) Theoretical calculations of γ-ray energies as a function of initial state angular momentum for $E2$ transitions for the prolate ^{178}Hg band and for the ^{177}Au strongly coupled band based on $1h_{11/2}$, $K = 9/2$ and $K = 11/2$ configurations.

note that a strongly coupled band has been reported in ^{181}Au [10]; however, without removal of transitions assigned to this band and changes to the spin assignments, it does not match the characteristics of the band discussed herein.

These results have been interpreted in terms of cranked Hartree-Fock-Bogoliubov (HFB) calculations based on a Skyrme energy functional. A microscopic description of rotational bands is obtained by introducing a so-called cranking constraint on the collective angular momentum. This approach has been applied successfully to study superdeformed bands in the $A \approx 190$ region [30]. The creation of a quasiparticle is treated self-consistently, which means that the polarization of the even-even vacuum on which the quasiparticle is created is fully taken into account [31]. The conditions of the calculation are the same as for the recent systematic study of the even-even nuclei in the neutron-deficient lead region using the SLy6 parametrization [4]. The use of alternative Skyrme functionals does not affect the results.

It should be noted that the assumptions of the cranked HFB approach do not allow for a precise assignment of angular momentum to a calculated level, especially at the bottom of a band. Indeed, there is no unique procedure to link the constraint on the collective rotation to the total angular momentum in the case of an odd nucleus where the quasiparticle also contributes to the spin. The relation that we have chosen is $J(J+1) = \langle \hat{J}_x \rangle^2 + K^2$, where $\langle \hat{J}_x \rangle$ is the mean value of the constrained component of the angular momentum and K is the expectation value of angular momentum of the blocked quasiparticle along the symmetry axis of the nucleus in the nonrotating configuration. However, similar to the other existing recipes, this relation is not well defined for $\langle \hat{J}_x \rangle \to 0$. Also, with increasing $\langle \hat{J}_x \rangle$ the deformation becomes slightly triaxial such that this recipe can also only be approximate at large spin.

The deformation energy curves of the Hg isotopes obtained with the SLy6 parametrisation have been published in Ref. [4]. These calculations predict the excitation energies of the oblate, nearly spherical, and prolate minima to be close in ^{178}Hg. Cranked HFB calculations of states for the three different minima lead to very different spin dependences of the γ-ray energies. For ^{178}Hg, only states in the prolate well lead to an agreement with experiment. The calculated states in this band are predicted to have an intrinsic electric cartesian quadrupole moment $Q_0 \sim 8.1\,e$b. The results obtained for the prolate minimum are plotted in Fig. 3(b). For ^{177}Au, we find two prolate bands with similar deformation, one based on a $K^\pi = 9/2^-$ level and the other on a $K^\pi = 11/2^-$, both originating from the spherical $1h_{11/2}$ shell. The band built on the $K^\pi = 9/2^-$ is predicted to have a lower excitation energy in our calculations. However, previous studies have shown that the relative placement of single-particle levels predicted by mean-field models does not always reproduce the relative position of band heads in odd-mass nuclei [32]. A small rearrangement of single-particle states at sphericity would change the order of levels in the second prolate minimum and bring the $K^\pi = 11/2^-$ member of $1h_{11/2}$ shell closer to the Fermi level. The calculated angular-momentum dependence of γ-ray energies for both prolate assignments in ^{177}Au resembles that of ^{178}Hg; see Fig. 3(b).

The similarity of the spin dependence of γ-ray energies in ^{178}Hg and ^{177}Au is a necessary condition to consider that one has a strongly coupled band in the Au isotope. It is not evident how to check in a fully self-consistent calculation that the angular momentum of ^{177}Au is generated by the rotation of a ^{178}Hg core, with the quasiparticle remaining unaffected. In order to get an impression of how the total angular momentum decouples into collective rotation and the intrinsic spin of the quasiparticle, we have analyzed three mean-field configurations, the noncranked band head of the $K^\pi = 9/2^-$ band and two of its cranked states at $J^\pi = 15/2^-$ and $27/2^-$, by projecting them on good angular momentum and particle number using the method presented in Refs. [33,34]. The two higher-spin states are slightly triaxial with triaxiality angles of $\gamma = 2.5^\circ$ and 8.5°, respectively. In all three cases, the $K^\pi = 9/2^-$ component dominates the decomposition of the wave function, from 99% at zero rotation to 55% at $J \approx 15/2$, and still 30% at $J \approx 27/2$, with no other component exceeding 10%. Although these calculations have to be treated with caution since there is no one-to-one correspondence between cranked mean-field states and the particle-rotor model, this is a strong indication that the cranked HFB wave function is dominated by the $K^{\pi} = 9/2^{-}$ quasiparticle.

In summary, a strongly coupled band in ^{177}Au and its decay paths to the $11/2^{-}$ α-decaying isomer have been observed. This configuration has a very low degree of rotational alignment relative to the prolate ^{178}Hg and ^{176}Pt core configurations. The results have been interpreted with cranked HFB calculations based upon a Skyrme energy functional. These calculations predict three coexisting structures for the ^{178}Hg core. Using the cranking model, we have shown that only states in the moderately deformed prolate well have moments of inertia with a dependence on energy similar to the data. In particular, quasiparticle excitations based on single-particle states originating from the $1h_{11/2}$ spherical subshell and with $K = 9/2$ or $11/2$ reproduce the data for ^{177}Au rather well. The rotational alignment of excited states based upon these configurations is very similar to those calculated for the cores. We interpret the strongly coupled band in ^{177}Au to be based on a configuration coupling a negative parity high-K proton hole with the unobserved 0_2^+ state in ^{178}Hg, which corresponds to a predicted low-lying prolate minimum. Although this configuration might be expected to follow the parabolic trend established for the excited 0_2^+ states in the core, its electromagnetic decay paths to the $11/2^{-}$ isomeric state are markedly different from those observed from the lowest deformed $11/2^{-}$ states in the ^{185}Au and ^{187}Au isotopes. On this basis, we conclude that a significant change in the structure of the underlying $^{A+1}$Hg core has occurred between ^{186}Hg ($N = 106$) and ^{178}Hg ($N = 98$). At present, attempting to give further interpretation for such an unexpected insight to the structure of the even Hg 0_2^+ core configurations seems premature. More detailed studies of $^{181-187}$Au are clearly mandated.

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